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On Practical Issue of Non-Orthogonal Multiple Access for 5G Mobile Communication

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Abstract

The fifth generation (5G) mobile communication has an impact on the human life over the whole world, nowadays, through the artificial intelligence (AI) and the internet of things (IoT). The low latency of the 5G new radio (NR) access is implemented by the state-of-the art technologies, such as non-orthogonal multiple access (NOMA). This paper investigates a practical issue that in NOMA, for the practical channel models, such as fading channel environments, the successive interference cancellation (SIC) should be performed on the stronger channel users with low power allocation. Only if the SIC is performed on the user with the stronger channel gain, NOMA performs better than orthogonal multiple access (OMA). Otherwise, NOMA performs worse than OMA. Such the superiority requirement can be easily implemented for the channel being static or slow varying, compared to the block interval time. However, most mobile channels experience fading. And symbol by symbol channel estimations and in turn each symbol time, selections of the SIC-performing user look infeasible in the practical environments. Then practically the block of symbols uses the single channel estimation, which is obtained by the training sequence at the head of the block. In this case, not all the symbol times the SIC is performed on the stronger channel user. Sometimes, we do perform the SIC on the weaker channel user; such cases, NOMA performs worse than OMA. Thus, we can say that by what percent NOMA is better than OMA. This paper calculates analytically the percentage by which NOMA performs better than OMA in the practical mobile communication systems. We show analytically that the percentage for NOMA being better than OMA is only the function of the ratio of the stronger channel gain variance to weaker. In result, not always, but almost time, NOMA could perform better than OMA.

Keywords: *NOMA, Rayleigh fading channel, Successive interference cancellation, Achievable rate region, Power allocation.*

1. Introduction

The fifth generation (5G) mobile wireless communication has influenced the human life over the whole world, nowadays, through the artificial intelligence (AI) and the internet of things (IoT) [1]. For the 5G mobile communication, the advanced high performance technologies are proposed by the international standardization bodies. Among them, non-orthogonal multiple access (NOMA) outperforms existing orthogonal multiple

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access (OMA), theoretically [2-4]. In [5], based on the optimization, the superiority of NOMA is presented. Also, the cooperative communication is applied to NOMA in [6].

The conventional OMA can be summarized as follows; the first generation (1G) wireless communication uses frequency-division multiple access (FDMA). And for the second generation (2G), time-division multiple access (TDMA) is adopted. Code-division multiple access (CDMA) is used by both 2G and the third generation (3G). The fourth generation (4G) is characterized by orthogonal frequency division multiple access (OFDMA) [7], [8]. In NOMA, multiple users are served in the same channel resources, such as a time slot or spreading code, to meet the 5G wireless communication demands on low latency and massive connectivity.

For the practical channel models, such as the fading channel models, performance analyses have been carried out intensively in the literature of NOMA [9-11]. The more advanced fading channel model is investigated in [12]. The superiority of NOMA over OMA is based on the condition that the successive interference cancellation (SIC) should be performed on the users of the stronger channel gains with the lower power allocation. Such the condition can be easily implemented for the fixed channel gain, or the slow varying fading channel, or the static channel gain. However, for the fast fading channel, which is the more practical channel model scenario, this superiority is based on the assumption that the channel estimation is performed symbol by symbol and the SIC is always performed on the user with stronger channel gain. In the practical systems, such schemes are not feasible. Then this paper calculates the probability for NOMA to outperform OMA. The paper is organized as follows. Section II defines the system and channel model. In Section III, such probabilities are calculated analytically. In Section IV, the results are presented and discussed. The paper is concluded in Section V.

1.1 Our Contribution Summary

Our new contributions are summarized as follows; first, we derive the mathematical expression for the superiority of NOMA over OMA, analytically, under the practical communication systems of the block transmission and the single channel estimation per block. Second, based on the derived analytical expression, we show that the superiority of NOMA over OMA is the function of the channel gain variance ratio. Third, one of the most important contributions of this paper is that the superiority is dependent on the absolute ratio of the channel gain variance, not the absolute difference. Such the fact implies that NOMA can be superior to OMA, even though all the channel gain variances are small.

2. System and Channel Model

Consider the discrete memoryless channel (DMC). Assume that the total transmit power is P, the power allocation factor is α with $0 \leq \alpha \leq 1$, ($0\% \leq \alpha \leq 100\%$), and the channel gains $h_1 \sim \mathcal{CN}\left(0, \Sigma_1\right)$ and $h_2 \sim \mathcal{CN}\left(0, \Sigma_2\right)$ are Rayleigh faded, with $\Sigma_1 > \Sigma_2$. The notation $\mathcal{CN}\left(\mu, \Sigma\right)$ denotes the complex circularly-symmetric normal distribution with mean μ and variance Σ. Then αP is allocated to the user-1 signal s_1 and $(1-\alpha)P$ is allocated to the user-2 signal s_2, with $\mathbb{E}\left[\left|s_1\right|^2\right] = \mathbb{E}\left[\left|s_2\right|^2\right] = 1$. The superimposed signal is expressed by

$$x = \sqrt{\alpha P} s_1 + \sqrt{(1-\alpha)P} s_2 . \tag{1}$$

Before the SIC is performed on the user-1 with the better channel condition, the received signals of the user-1 and the user-2 are represented as

$$\begin{aligned} z_1 &= h_1\sqrt{\alpha P}s_1 + \left(h_1\sqrt{(1-\alpha)P}s_2 + w_1\right) \\ z_2 &= h_2\sqrt{(1-\alpha)P}s_2 + \left(h_2\sqrt{\alpha P}s_1 + w_2\right) \end{aligned} \tag{2}$$

where w_1 and $w_2 \sim \mathcal{CN}\left(0, N_0\right)$ are complex additive white Gaussian noise (AWGN) and N_0 is one-sided power spectral density. Moreover, if the 1-dimensional modulation constellation is considered, the following metrics are sufficient statistics;

$$\begin{aligned} r_1 &= \left|h_1\right|\sqrt{\alpha P}s_1 + \left(\left|h_1\right|\sqrt{(1-\alpha)P}s_2 + n_1\right) \\ r_2 &= \left|h_2\right|\sqrt{(1-\alpha)P}s_2 + \left(\left|h_2\right|\sqrt{\alpha P}s_1 + n_2\right) \end{aligned} \tag{3}$$

where n_1 and $n_2 \sim \mathcal{N}\left(0, N_0 / 2\right)$ are AWGN. The notation $\mathcal{N}\left(\mu, \Sigma\right)$ denotes the normal distribution with mean μ and variance Σ. In the standard NOMA, the SIC is performed only on the user-1. Then the received signal is given by, if the perfect SIC is assumed,

$$y_1 = r_1 - \left|h_1\right|\sqrt{(1-\alpha)P}s_2 = \left|h_1\right|\sqrt{\alpha P}s_1 + n_1. \tag{4}$$

Then the achievable rates are given in [bits/(real) channel use] by

$$\begin{aligned} R_1 &\le \frac{1}{2}\log_2\left(1 + \frac{\left|h_1\right|^2 \alpha P}{N_0 / 2}\right) \\ R_2 &\le \frac{1}{2}\log_2\left(1 + \frac{\left|h_2\right|^2 (1-\alpha)P}{\left|h_2\right|^2 \alpha P + N_0 / 2}\right). \end{aligned} \tag{5}$$

3. Probability Derivation

Assuming the total transmit signal power to one-sided power spectral density ratio $P / N_0 = 20$, we plot the achievable rate regions of NOMA and OMA with $\left|h_1\right| = \sqrt{9.9} \simeq 3.14$ and $\left|h_2\right| = \sqrt{0.1} \simeq 0.31$, in Fig. 1.

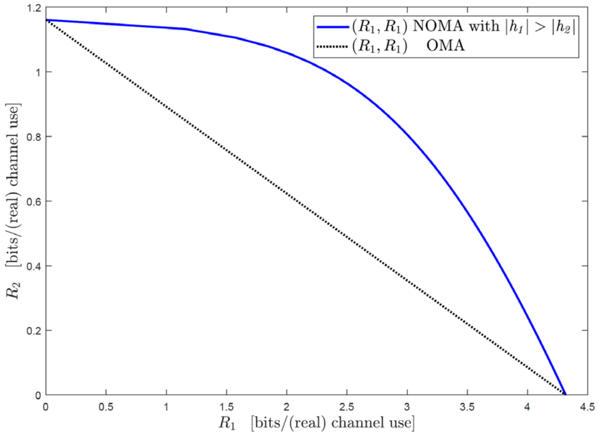

Figure 1. Comparison of achievable rate regions of NOMA and OMA ($\left|h_1\right| > \left|h_2\right|$).

It is observed that NOMA outperforms OMA. On the other hand, with the same channel gain realizations, if SIC is performed on the weaker channel user, NOMA performs worse than OMA, shown in Fig. 2.

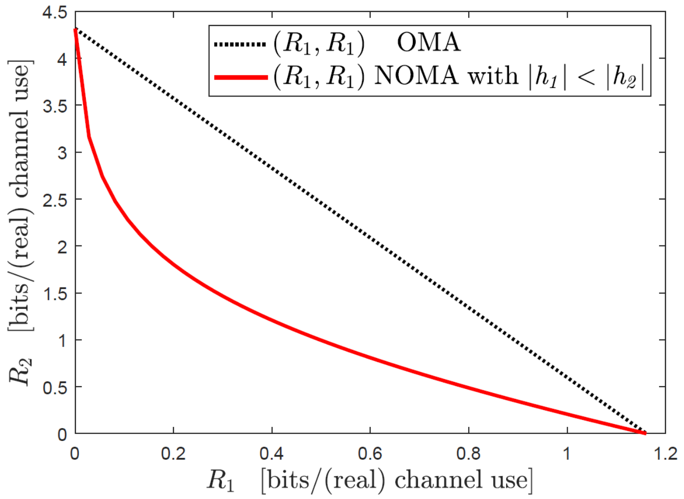

Figure 2. Comparison of achievable rate regions of NOMA and OMA ($|h_1| < |h_2|$).

Therefore, we consider all possible cases for the channel gain realizations h_1 and h_2. Among those events, only when $|h_1| > |h_2|$, NOMA outperforms OMA. Note that $|h_1| = |h_2|$ implies that NOMA performs exactly the same as OMA. Furthermore, when $|h_1| < |h_2|$, NOMA performs worse than OMA. From such observations, we calculate the probability for NOMA to outperform OMA as follows.

$$\begin{aligned} &\int_0^\infty \frac{1}{\Sigma_1} e^{-\frac{\gamma_1}{\Sigma_1}} \int_0^{\gamma_1} \frac{1}{\Sigma_2} e^{-\frac{\gamma_2}{\Sigma_2}} d\gamma_2 d\gamma_1 \\ &= \int_0^\infty \frac{1}{\Sigma_1} e^{-\frac{\gamma_1}{\Sigma_1}} \left[-e^{-\frac{\gamma_1}{\Sigma_2}} + 1 \right] d\gamma_1 \\ &= \frac{\Sigma_1}{\Sigma_1 + \Sigma_2} \\ &= \frac{\Sigma_1 / \Sigma_2}{\Sigma_1 / \Sigma_2 + 1} \end{aligned} \tag{6}$$

where $\gamma_1 = |h_1|^2$ and $\gamma_2 = |h_2|^2$ are exponentially distributed. Note that $|h_1| > |h_2|$ implies $|h_1|^2 > |h_2|^2$. In (6), for the given γ_1, we integrate $\frac{1}{\Sigma_2} e^{-\frac{\gamma_2}{\Sigma_2}}$ from 0 to γ_1. And γ_1 moves from 0 to ∞.

4. Results and Discussions

In Fig. 3, we plot the probability for NOMA to outperform OMA.

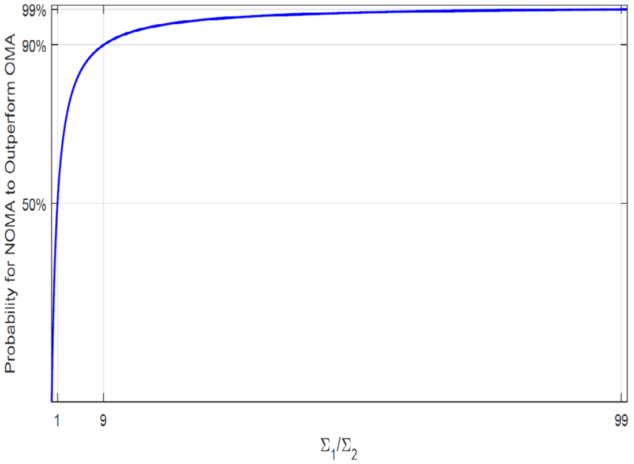

Figure 3. Probability for NOMA to outperform OMA as a function of Σ_1 / Σ_2.

First, if $\Sigma_1 / \Sigma_2 = 1$, i.e., equal channel gain variances, the percentage is 50%, which confirms the previous research results; when the channel gains are equal, NOMA has no gain over OMA. Second, if $\Sigma_1 / \Sigma_2 = 9$, then NOMA performs better than OMA, by 90%. Third, if $\Sigma_1 / \Sigma_2 = 99$, then NOMA outperforms OMA, by 99%. Such observations suggest that in order for NOMA to be used instead of OMA, it is desirable for Σ_1 / Σ_2 to be large enough. As the last comment, the performance superiority depends only on the ratio, not the absolute difference; from this experience, even though the both channel gains are very weak, if the ratio is very large enough, NOMA could be a good choice.

4.1 Main Contribution

For the practical systems with the block-wise channel estimations, not the symbol-wise channel estimations, the superiority of NOMA over OMA is dependent on the channel gain variance ratio, not the absolute difference of them. One of the important applications of the result is that even when all the channel gain variances are poor, NOMA can be comparable to OMA.

5. Conclusion

We calculated the probability for NOMA to outperform OMA in the practical mobile system. We noted that the channel estimation could not be performed symbol by symbol, but one time each block of symbols, in the practical mobile communication system. The SIC was performed based on the block-wise estimated channel gains. In that case, NOMA did not always outperform OMA. First, we derived an analytical expression for the NOMA's superiority by the double integration of the probability density functions of channel gains. It was shown that with the channel gain variance ratio being 9, NOMA outperforms OMA by 90%. In addition, when the channel gain variance ratio is 99, the probability of the NOMA's superiority over OMA is 99%. The one of our main contributions is that such superiority is dependent on the ratio of the channel gain variances, not the difference of them. This implies that even when all the channel gains are weak, if the ratio is large enough to satisfy the system requirement, NOMA could be a good candidate for the 5G mobile communication.

In result, the channel gain variance ratio would be a design criterion for NOMA, compared to OMA.

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